

## RADIOISOTOPE POWER SYSTEMS PROGRAM

NASA SPECIAL SESSION: NEXT-GENERATION RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG)
DISCUSSION

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www.nasa.gov

2021

2011

1971

## Purpose of this Session

- Provide Background on the Next Generation RTG Study results
- Discuss current NASA investments in TE technologies
- 1971 Initiate discussion with TE and RPS community on potential plans for technology maturation of a Next Generation RTG
  - Discuss upcoming RFI and potential RFP

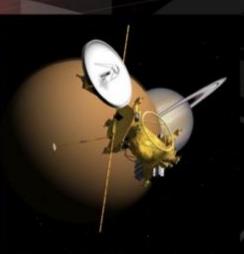
## Agenda

- Background
- Next-Generation RTG Study
- TE Materials and Technology
- NASA conceptual plan forward
- Q&A

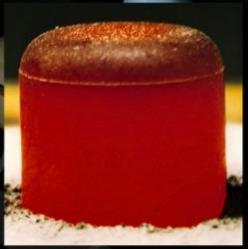
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RADIOISOTOPE POWER SYSTEMS PROGRAM **BACKGROUND** Pre-Decisional for Discussion Only 

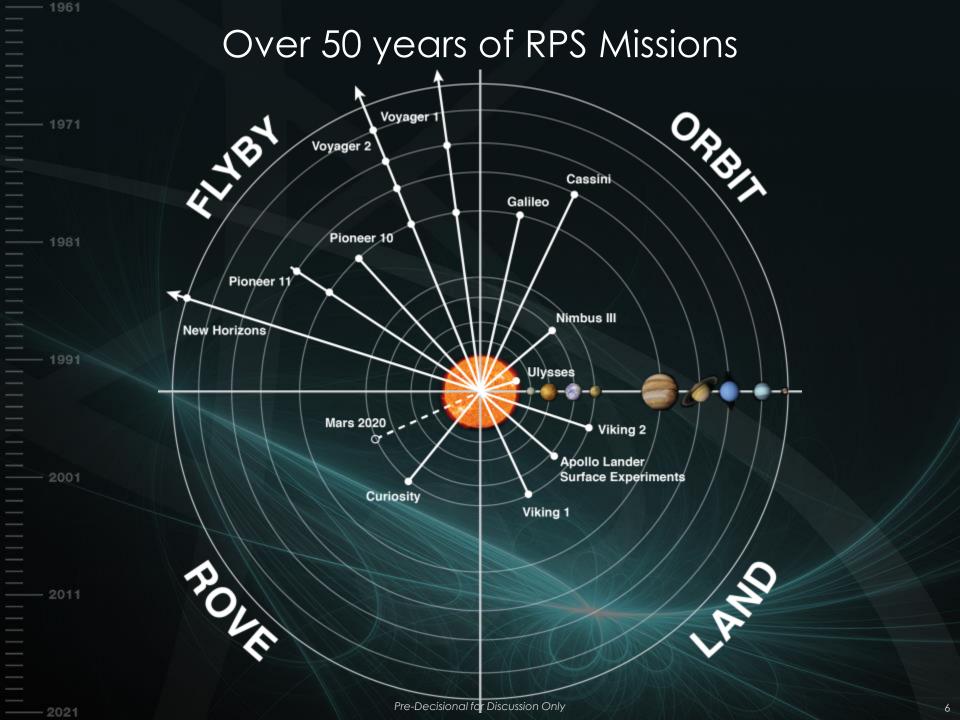
## Radioisotope Power Systems







- Enable and enhance missions by providing electrical power to explore remote and challenging environments where solar power is unavailable
  - Spacecraft operation
  - Instrumentation
- Converts heat from a Radioisotope into electricity
  - Heat is the product of the natural decay process of the isotope



## RPS Objective and Level I Requirements

### Program Objective

 Ensure the availability of RPS for the exploration of the solar system in environments where conventional solar or chemical power generation is impractical or impossible.

### Program Level I Requirements

- PCA-1: The RPS Program shall procure RPS for SMD missions.
- PCA-2: The RPS Program shall sustain the capability to conduct RPS missions.
- PCA-3: The RPS Program shall develop RPS technologies for insertion into flight systems.
- PCA-4: The RPS Program shall manage the nuclear launch safety approval process for RPS.

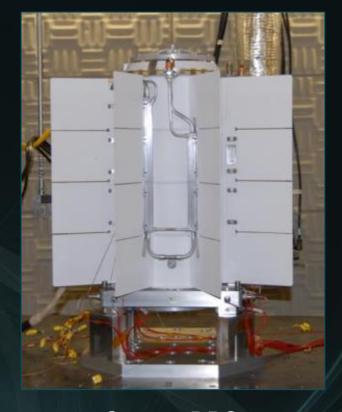
## Flight Systems for Current Missions



General Purpose Heat
Source – Radioisotope
Thermoelectric Generator
(GPHS–RTG)

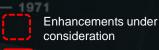


Multi-Hundred Watt –
Radioisotope
Thermoelectric
Generator (MHW–
RTG)



Current RPS:
Multi-Mission
Radioisotope
Thermoelectric Generator
(MMRTG)

## The eMMRTG: What is being enhanced?



Known enhancements

#### Engineering:

1961

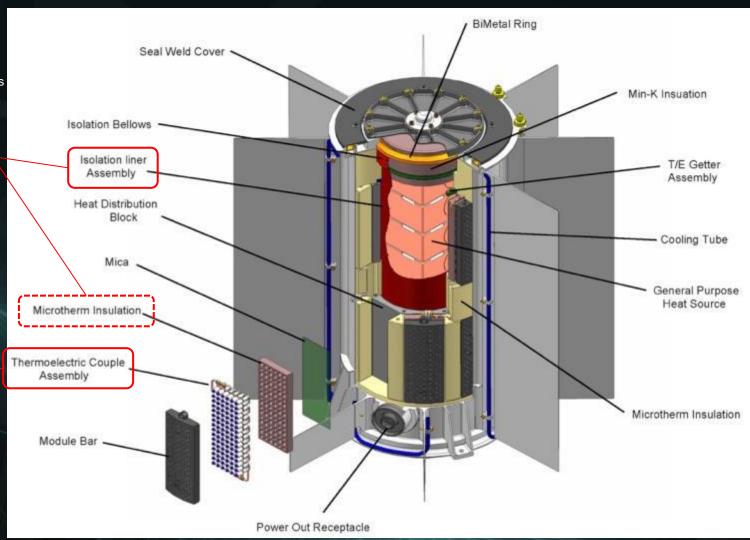
- emissivity change to liner,
- substitute insulation



Changes needed to MMRTG



New Technology: Substitute SKD thermoelectric couples



## Next-Generation RTG Study Objectives

Determine the characteristics of a Next-Generation RTG that would "best" fulfill Planetary Science Division (PSD) mission needs. This study is limited to systems that convert heat to electricity using thermocouples. "Best" is defined as a confluence of the following factors:

- An RTG that would be useful across the solar system
- An RTG that maximizes the types of potential missions: flyby, orbiter, lander, rover, boats, submersibles, balloons
- An RTG that has reasonable development risks and timeline
- An RTG that has a value (importance, worth and usefulness) returned to PSD that warrants the investment as compared with retaining existing baseline systems

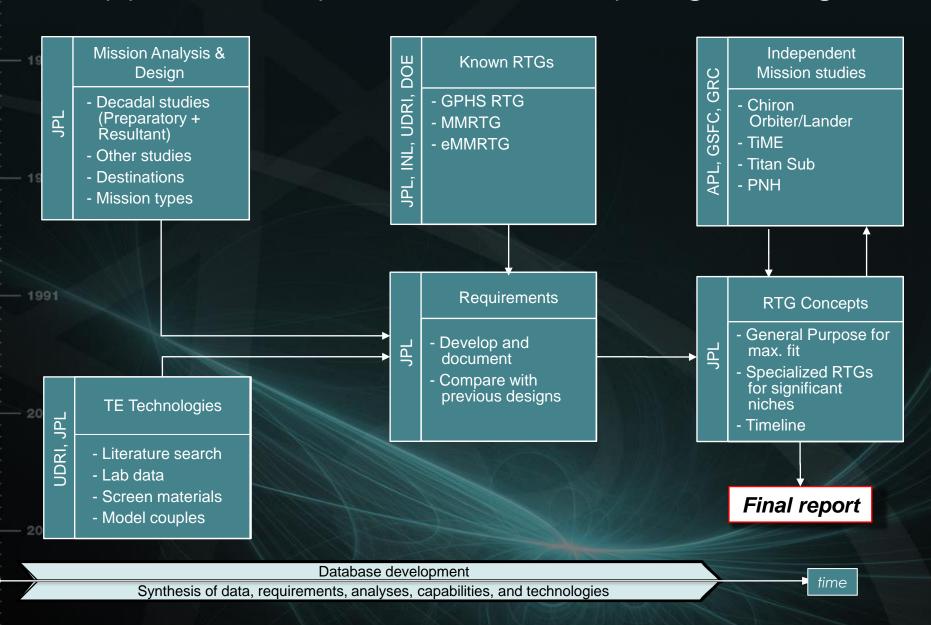
1971 Radioisotope Power Systems Program **NEXT-GENERATION RTG STUDY** 1991 2001 2011 Pre-Decisional for Discussion Only

## Next-Generation RTGs for NASA – Topics

- Approach
- Mission Analysis Overview
- Radioisotope Thermoelectric Generators (RTGs)
- RTG Design Trades and Risks
- Next-Generation RTG Concepts
- Summary of findings

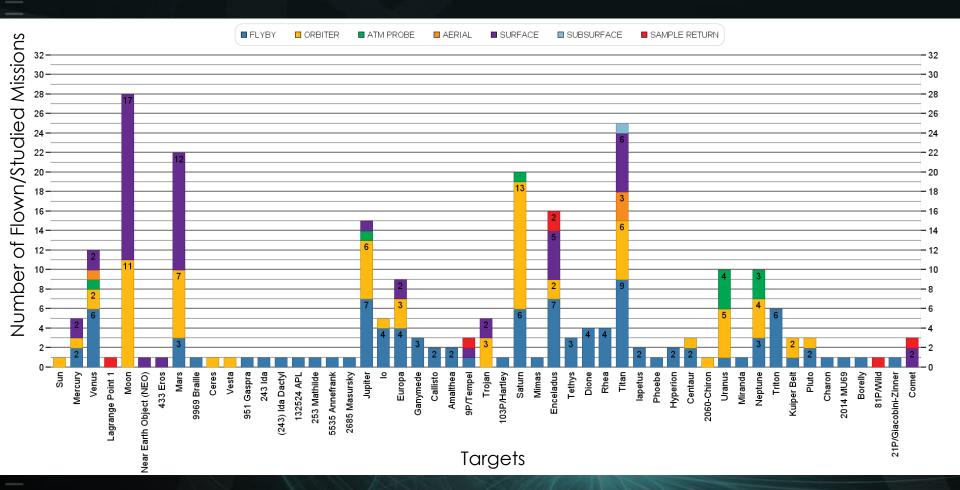
2001

## Approach – Top-Down+Bottom-up Engineering



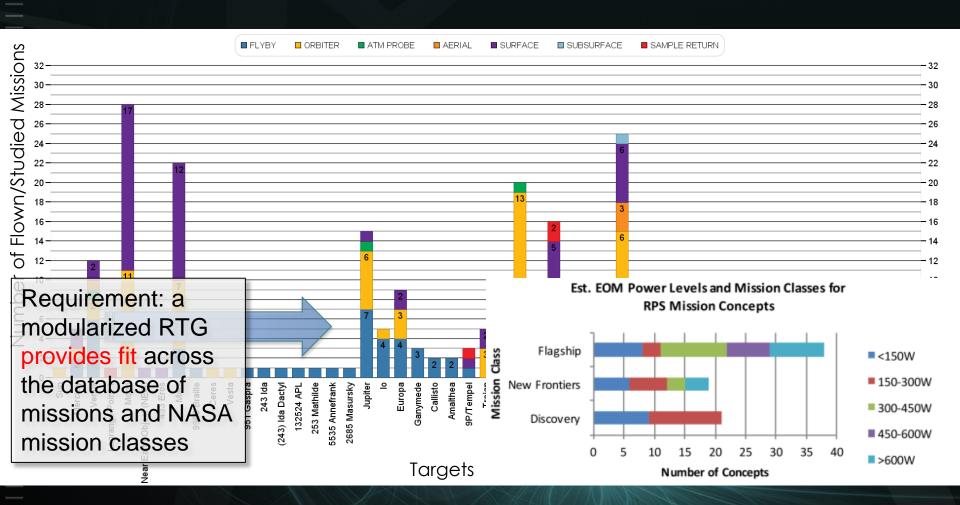
## Next-Generation RTGs for NASA Mission Analyses (MA)

### 249 Mission Studies in database



## Next-Generation RTGs for NASA Mission Analyses (MA)

Example of a requirement derived from Mission Analyses



### **Process**

#### **Destinations (63)**

(Visited or suggested in Decadal Surveys)

#### MMRTG/eMMRTG Req.



#### **GPHS-RTG Req.**

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#### Requirements I (MMRTG, GPHS-RTG)

Performance

**Physical** 

Structural

Environmental

# **Jupiter**

Venus

"Gas"



"Ocean"

Neptune

"Ice"

### Requirements II

(Alignment: Destination, Spacecraft/ Mission, Mission Types, Launch vehicles)

Performance

**Physical** 

Structural

Environmental

#### Draft **Requirements Tables**

Performance

**Physical** 

Structural

Environmental

### Spacecraft/Missions (99) /Mission Types

(Flown and Studied)



Cassini (Orbiter) "Flown"



Venus Rover (Surface) "Suggested"



Titan Submarine (Subsurface) "Suggested"

Titan IV B Launched:



Launch Vehicles (4)

Atlas V (541) Launched: MSL



Delta IV Heavy Potential Launcher

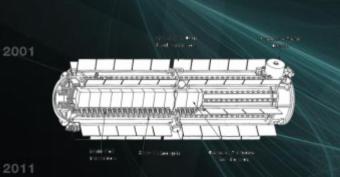


SLS (1 A and B) Potential Launcher

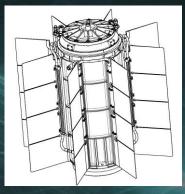
Pre-Decisional for Discussion Only

## Next-Generation RTGs for NASA Reference RTGs See Appendix N also

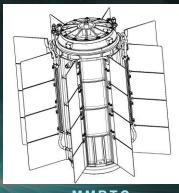
Acronym	Definition	Descriptions	Power/GPHS	Th, °C
GPHS-RTG	General-Purpose Heat Source RTG	This RTG was designed to operate in vacuum only. It was flown on PNH, Cassini, and other missions. Not a modular system.	290/18	1000
MMRTG	Multi-Mission RTG	Operates in vacuum and atmosphere. Flown on the Curiosity rover. Not a modular system.	110/8	530
eMMRTG	enhanced Multi-Mission RTG	A potential enhanced version of the MMRTG. Designed to operate in vacuum and atmosphere. Not a modular system. While not yet approved for development, it is extremely well modeled and its system-level requirements are well understood.	145/8	600



**GPHS RTG** 



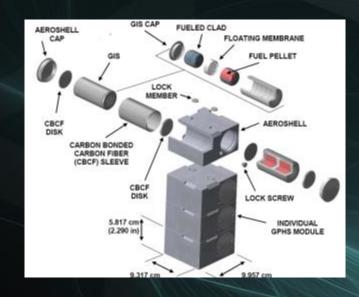
MMRTG

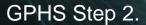


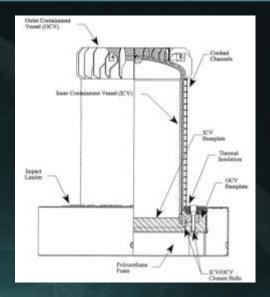
eMMRTG

## Next-Generation RTGs for NASA Architectural Trades and Design Constraints

Architectural Trades	Motivation
Couple Segmentation	Maximize couple performance
Cold Systems	Optimize for thermally sensitive environments
Modular Systems	Optimize radioisotope consumption, ease spacecraft integration, and closely match power available with power needs
Hybrid Systems	Maximize utility across the solar system



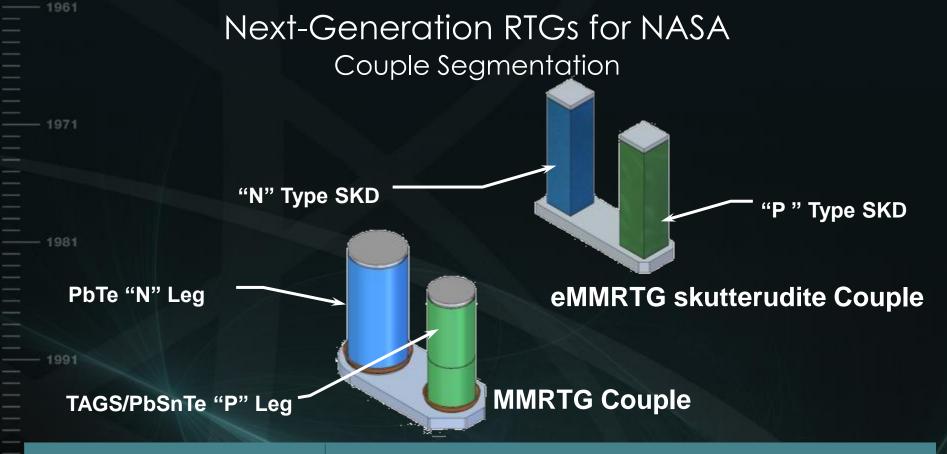




DOE Shipping Cask 9904. Usable internal dimensions: 81 cm in diameter by 135 cm in height.

1991

2001



Risk increases with increasing segmentation.

Each segment will have two or more mechanical interfaces each with a potential for CTE mismatch, and by adding more segments, designers add more materials composed of different molecules whose segments multiple the risk of CTE mismatch. In addition, each segment will have its own degradation performance that will have to be engineered. These things make clear risk will increase with increasing segmentation. It was noted that no RTG manufacturer has ever flown a TEC composed of legs with three segments.

CTE mismatch between segments can rapidly increase couple design complexity.

The temperature range over which a couple and all of its internal interfaces must operate is from room temperature to  $\sim 1,000$ °C on the hot-side and then back to room temperature. This cycle will be repeated a handful or more times during ground operations before the RTG's couples are finally heated, one last time, to  $\sim 1,000$ °C. CTE mismatch can require relatively exotic solutions and it can be eliminated from the risk list by material selection.

## Next-Generation RTGs for NASA "Cold" RTGs

- Cold RTGs were devised to minimize housing temperature to ease spacecraft integration and maximize power
- Three options were available: use triple-segmented couples operating near 1000 °C, use double-segmented couples near 600 °C, or use couples spanning a smaller temperature range such as 800 °C to 50 °C.

Risk increases with increasing segmentation.

Each segment will have two or more mechanical interfaces each with a potential for CTE mismatch, and by adding more segments, designers add more materials composed of different molecules whose segments multiple the risk of CTE mismatch. In addition, each segment will have its own degradation performance that will have to be engineered. These things make clear risk will increase with increasing segmentation. It was noted that no RTG manufacturer has ever flown a TEC composed of legs with three segments.

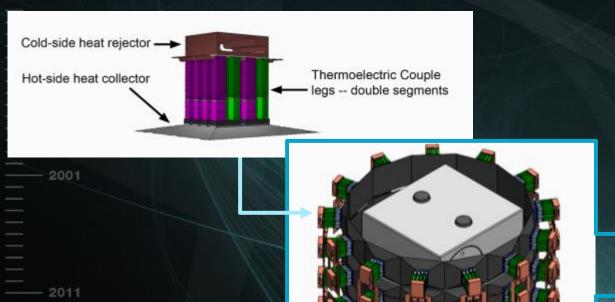
CTE mismatch between segments can rapidly increase couple design complexity.

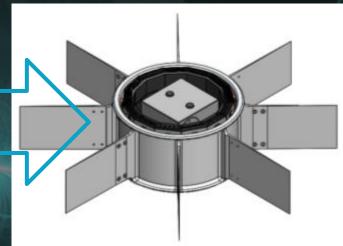
The temperature range over which a couple and all of its internal interfaces must operate is from room temperature to  $\sim 1,000^{\circ}\text{C}$  on the hot-side and then back to room temperature. This cycle will be repeated a handful or more times during ground operations before the RTG's couples are finally heated, one last time, to  $\sim 1,000^{\circ}\text{C}$ . CTE mismatch can require relatively exotic solutions and it can be eliminated from the risk list by material selection.

## Next-Generation RTGs for NASA Modularization

The degree of modularization at the system level can have a strong bearing on the risk of success or failure.

The more extensive modularization is, or the higher the degree of modularization, the more complex a generator's design and the greater number of interfaces it will include. That is, a generator whose design of the housing is assembled from lower-level assemblies, whose circuit follows suit, and whose TECs are modularized, maximizes the design challenges and interfaces. More interfaces can typically be a measure of added risk. For example, if an RTG consisted of a single GPHS surrounded by TECs and each of those RTGs would have to be integrated to produce more powerful generators, the number of mating tasks would be multiplied and so to the opportunity for problems.





## Next-Generation RTGs for NASA Hybridization

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Hybridization incurs risk by being responsive to too many functional requirements, that is, it risks failure while trying to satisfy all users.

Too many requirements can increase engineering focus on development of system-level solutions. This compounds the risk to an RTG system by increasing design and manufacturing challenges while potentially increasing risk in thermoelectric couple technologies for this variety of Next-Generation RTG concepts. As examples,

- Guaranteeing hermeticity for the life of an RTG is a challenge.
- Many of the components in an MMRTG-like design, a known design that works, must be discarded to provide a lightweight system requiring designers to create new system-level solutions. No such RTG exists for spaceflight.

2001

# Next-Generation RTGs for NASA Types and Features

Hybrid Cold Modular Segmented (TECs) (Operates in vacuum RTG Type/Acronym (lower cold-side (at the system-level) temperature) and atmospheres) Χ **SRTG SMRTG** Χ Χ **CSRTG** Χ Χ **CSMRTG** Χ Χ Χ Χ Χ Χ **HSMRTG** Χ Χ Χ Χ **CHSMRTG** 

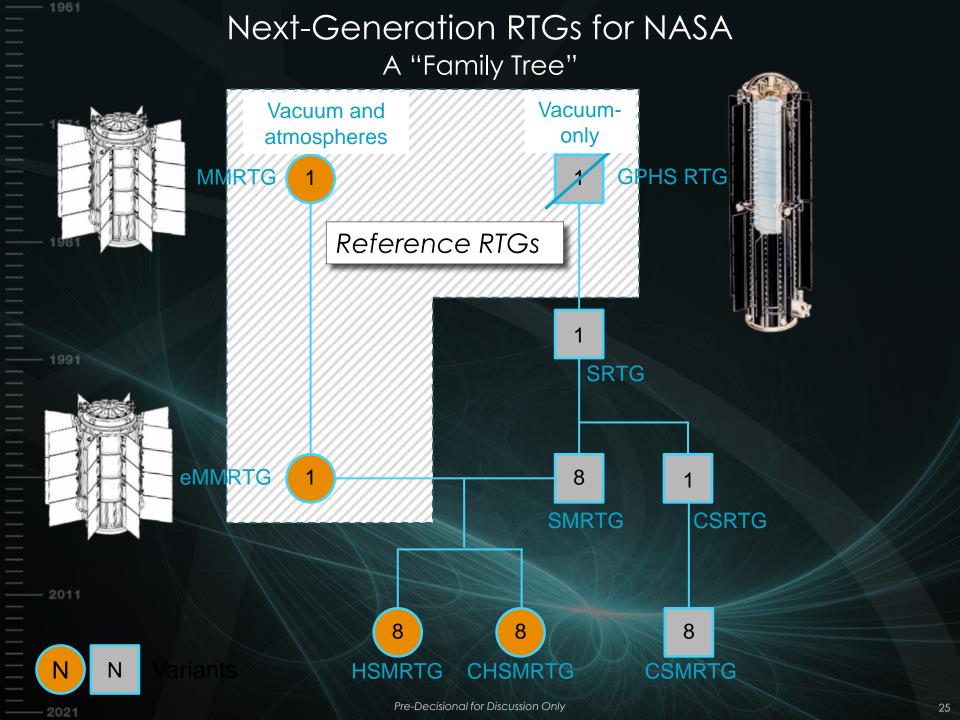
It should be clear that adding features increases risk

2011

2001

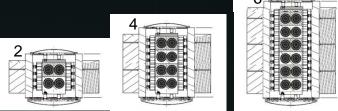
# Next-Generation RTGs for NASA What is in a name?

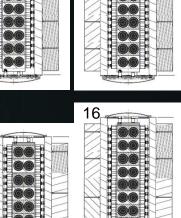
Prefix	Definition	Description
S	Segmented	An SRTG concept would use segmented TECs to boost power and would be a single size, in this case one built around 16 GPHS. No system-level modularity. Optimized for specific power. Operates only in vacuum.
SM	Segmented-Modular	An SMRTG concept uses segmented TECs built into housings that could be procured in differing sizes and hence was modularized at the system level. The size of the variant conceived of in this study was based upon the smallest sized RTG using 2 GPHS. RTGs built around 2, 4, 6, 8, 10, 12, 14, and 16 GPHSs would be possible. Operates only in vacuum.
CS	Cold-Segmented	A CSRTG concept designed to the cold-side of the RTG operated at significantly colder temperatures than is typical. This single-sized RTG would be built around 16 GPHS. No system-level modularity. Optimized for specific power. Operates only in vacuum.
CSM	Cold-Segmented- Modular	This generator concept uses the same couples as the SMRTG except that BiTe segments have been added to boost power and lower the cold-side operating temperature. The size of the variant conceived of in this study was based upon the smallest sized RTG using 2 GPHS. RTGs built around 2, 4, 6, 8, 10, 12, 14, and 16 GPHSs would be possible. Operates only in vacuum.
нѕм	Hybrid-Segmented Modular	This HSMRTG would use segmented TECs in a sealed and evacuated vessel and modularize the system. The size of the variant conceived of in this study was based upon the smallest sized RTG using 2 GPHS. RTGs built around 2, 4, 6, 8, 10, 12, 14, and 16 GPHSs would be possible. Operates in vacuum and atmospheres.
CHSM	Cold-Hybrid, Segmented-Modular	Combines the HSMRTG with a segmented TEC whose segments were designed to allow the generator to operate at significantly lower cold-side temperatures. Operates in vacuum and atmospheres. RTGs built around 2, 4, 6, 8, 10, 12, 14, and 16 GPHSs would be possible.

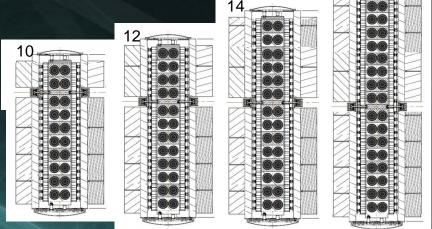


## Next-Generation RTGs for NASA Concepts

- Types of new RTG Concepts:
  - Vacuum Only
    - Segmented (TECs)
    - Cold Segmented
    - Segmented-Modular
    - Cold Segmented-Modular
  - Vacuum and Atmosphere
    - Hybrid Segmented-Modular
    - Cold Hybrid Segmented-Modular
- Variants: 2, 4, 6, 8, 10, 12, 14, and 16 GPHS

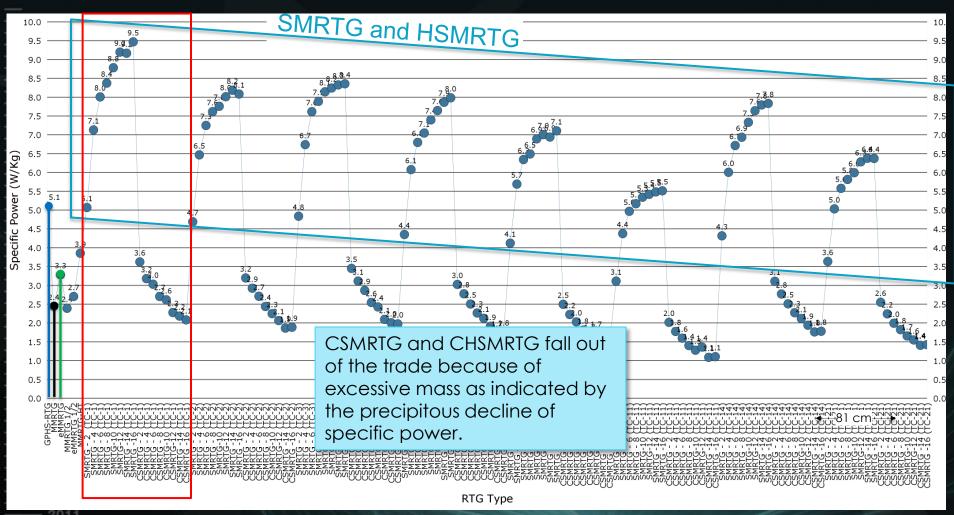






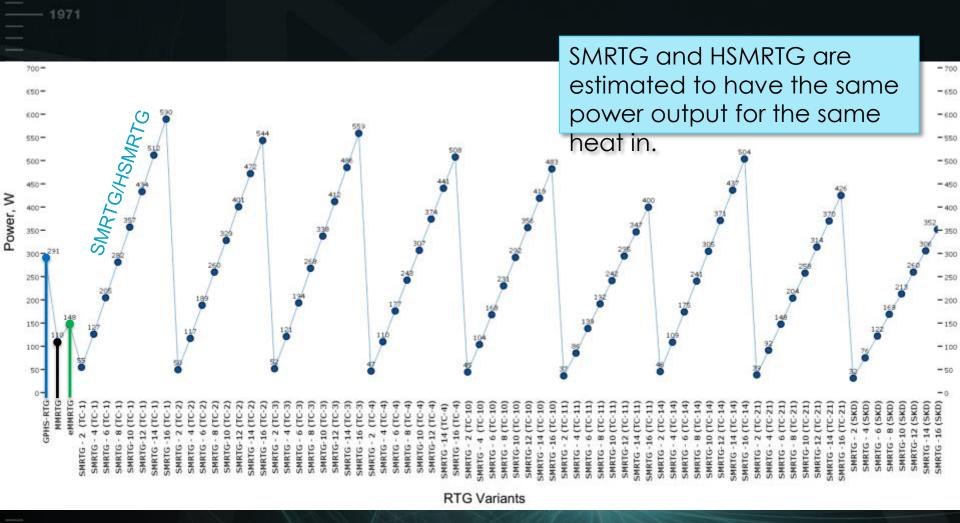
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## Next-Generation RTGs for NASA Specific Power

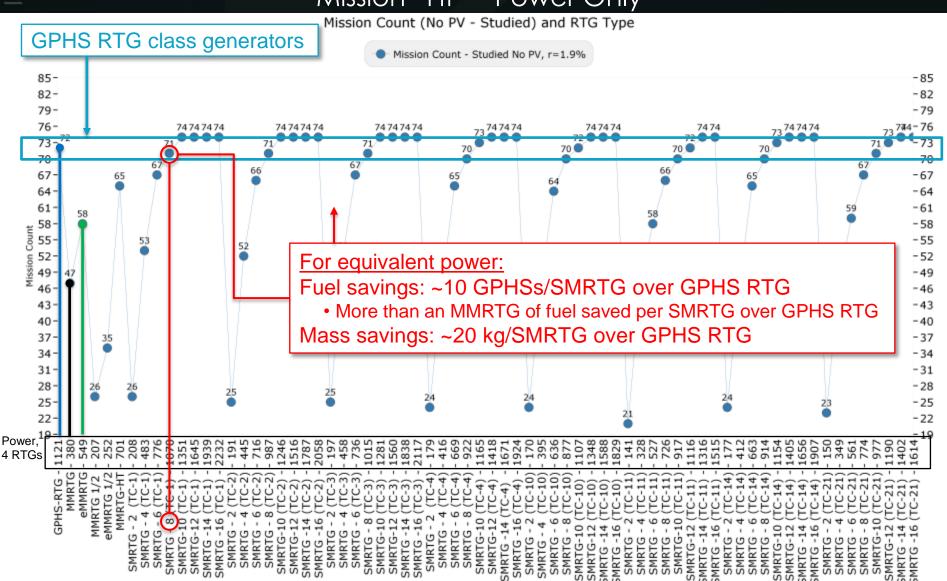


"Cold" concepts all suffer from extreme masses due to fin size to achieve "cold" temperatures. RTGs using 8 or more GPHSs do not fit in the shipping container.

## Next-Generation RTGs for NASA Power

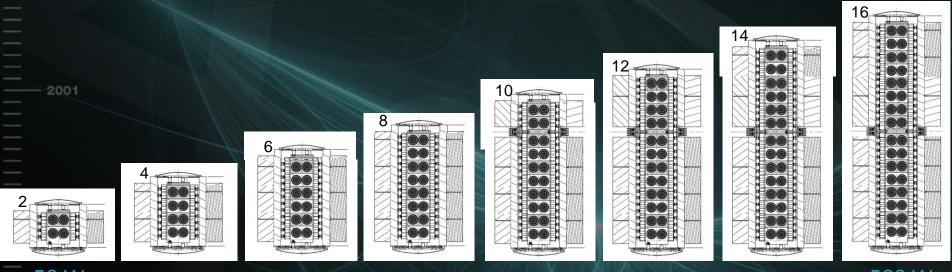


## Next-Generation RTGs for NASA Concepts Mission "Fit" – Power Only



## Next-Generation RTGs for NASA Concepts

- Three surviving Types of new, general-purpose RTG Concepts:
  - Vacuum Only
    - Single-point design
    - Modular
  - Vacuum and Atmosphere
    - Hybrid
- Variants: 2, 4, 6, 8, 10, 12, 14, and 16 GPHS variants



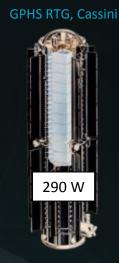
**Next-Generation RTG** 

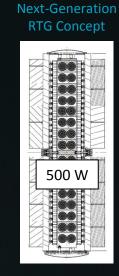
## Next-Generation RTGs for NASA Concepts

MMRTG, Curiosity

110 W







Power, launch, W	110	150	290 (880)	500
Power, end of life, W	55	91	213 (640)	362
Degradation rate, av	4.8%	2.5%	1.9%	1.9%
# GPHSs	8	8	18	16
Length, m	0.69	0.69	1.14	1.04
Mass, kg	45	44	57	62

1961

1971

### Next-Generation RTGs for NASA Overview of Recommendations

- Complete eMMRTG
  - Continue with skutterudite thermoelectric couple
  - Carry development to eMMRTG Qualification Unit
- Initiate Next-Generation RTG System
  - Vacuum-only
  - Modular

1971

2001

- 16 GPHSs (largest RTG variant)
- $PBOM = 400-500 W_e$  (largest RTG variant)
- Mass goal of < 60 kg (largest RTG variant)</li>
- Degradation rate < 1.9 %</li>

RADIOISOTOPE POWER SYSTEMS PROGRAM TE MATERIALS AND **TECHNOLOGY** Pre-Decisional for Discussion Only 

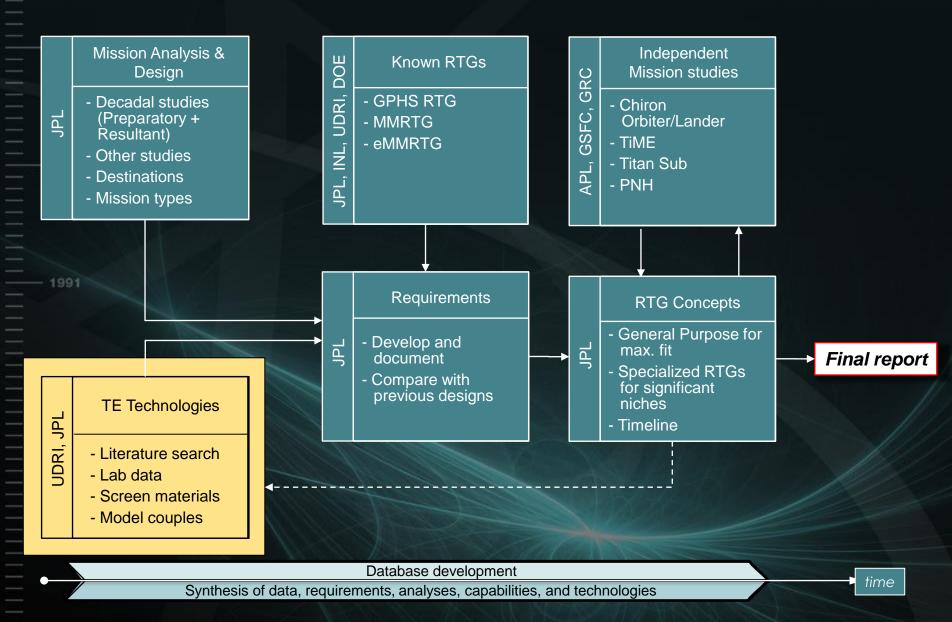
## Outline

- Approach for Next Generation RTG Technology Evaluation
- TE technologies for RPS: background
- Advanced TE technologies for Next-Generation RTG study
- Summary

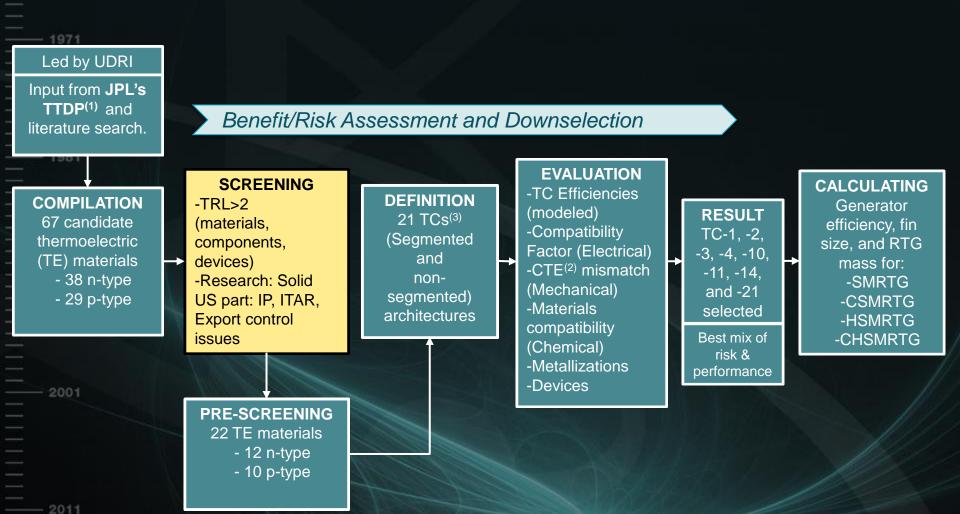
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## Overall Approach

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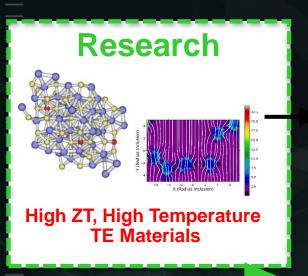


## Thermoelectric Technologies: Screening, Evaluation, and Selection



- (1) TTDP: Thermoelectric Technology Development Program, managed under the NASA's Radioisotope Power System (RPS) Program. The TTDP routinely evaluates potential thermoelectric candidate technologies
- (2) CTE: Coefficient of Thermal Expansion
- (3) TC: Thermoelectric couple

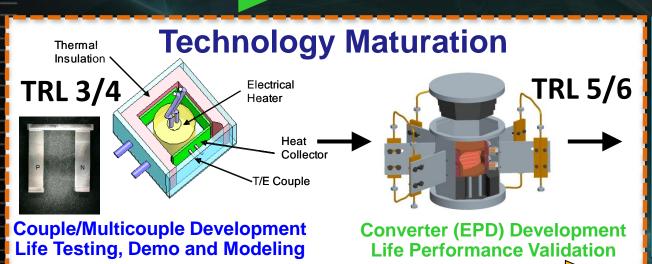
## RTG Technology Lifecycle

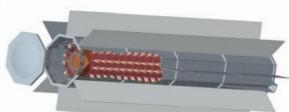




NASA/Academia

NASA/Academia/Industry





TRL 6 → TRL 8

Engineering & Qualification
System Development &
Performance Validation

NASA/Industry/DOE

DOE/Industry/NASA

## RTG: Thermoelectric Technology Nomenclature

Heat source

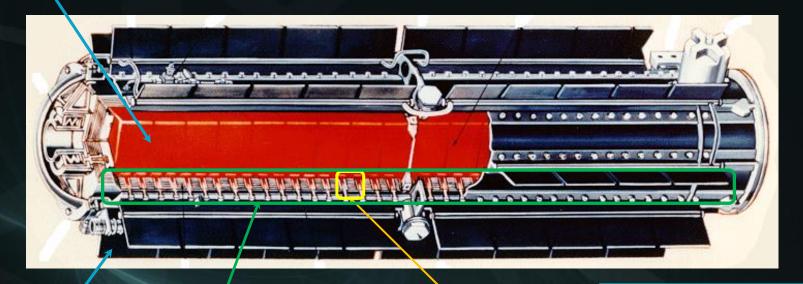
1981

1991

2001

2011

2021



Radiator

Thermoelectric Converter (array of couples and its support structure/interfaces to heat source and radiator)

Thermoelectric Couple



Hot Shoe (Heat collector, electrical interconnect)

TE elements

(TE materials, metallizations, diffusion barriers)

Cold Shoe (Electrical interconnect, Dielectric layer, cold side attachment)

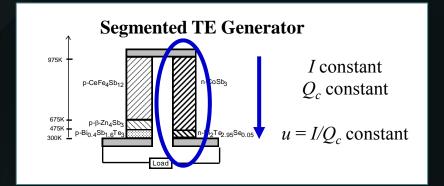
## High Efficiency = High ZT & Wide DT

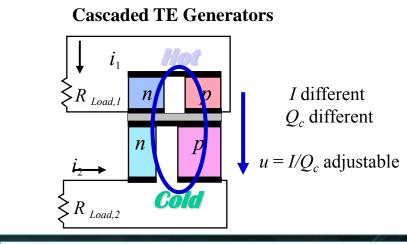
- Need to combine several TE materials
- Segmenting vs. Cascading
  - Segmented Thermoelectric
    - Constrained by constant current
      - u = I/Qc ≈ Constant
  - Cascaded Thermoelectric

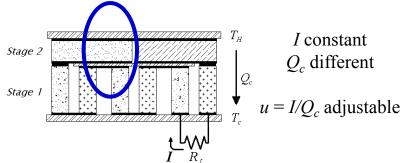
1991

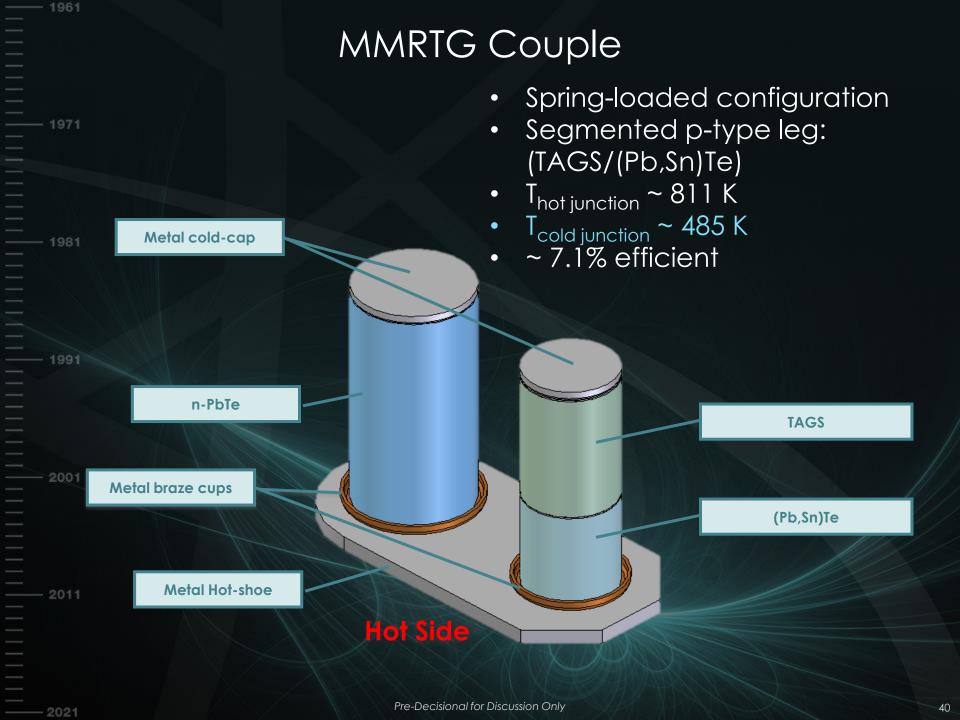
2001

- Independent circuits for each stage
  - Current different in each stage
  - Heat different in each leg
  - u optimized for each stage
- Both methods maximize ZT (efficiency) across wide  $\Delta T$ , but segmenting has been preferred method for space power systems
- Expectation is that segmented technology is required to achieve high efficiency goal for Next Generation RTG

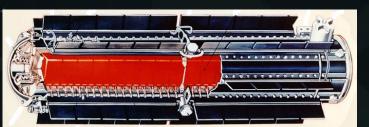




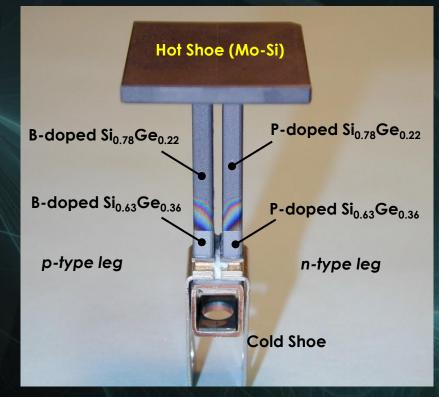




## **GPHS-RTG** Couple



- Cantilevered configuration Segmented Legs
  - Higher Ge content on lower segment
  - $T_{\text{hot junction}} \sim 1273 \text{ K}$   $T_{\text{cold junction}} \sim 573 \text{ K}$
- 7.5% efficient



1991

2001

# TE Materials & Device Technologies for Next Generation RTG Study

## Key attributes

- A high figure of merit (ZTmax > 1) within the temperature range of interest
- A high likelihood of maintaining chemical and mechanical stability within the temperature range of interest
- A high likelihood that the thermoelectric transport properties (Seebeck coefficient, electrical conductivity, and thermal conductivity) would remain stable over the targeted operating lifetime (> 17 years)
- Ability to be integrated into efficient thermoelectric devices
   (≥12%), either in unsegmented or in segmented configuration
- Ability to proceed to a technology maturation phase with reasonably low programmatic risk.

## Key criteria

- Technology readiness level
- Material systems

# Next Generation RTG TE Technologies Phase Space

#### **Device Technologies**

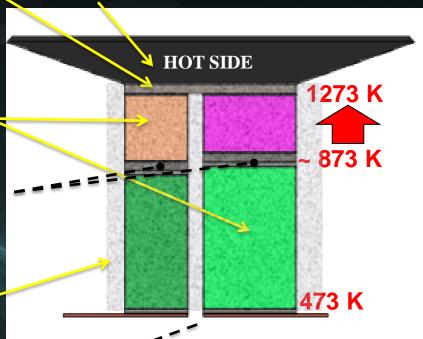
Mechanically robust & chemically stable, low contact resistance hot side metallizations

Mechanically robust & thermally stable materials

Mechanically compliant, high electrical/thermal conduction segment interfaces

Practical, effective thermal insulation / sublimation suppression

Long term stability of hot shoe



#### **Materials**

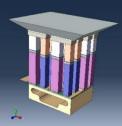
#### Advanced complex materials

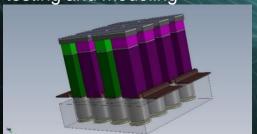
- Zintls
  - 14-1-11
    - 1-2-2
    - 9-4-9
- Chalcogenides
  - La<sub>3-x</sub>Te<sub>4</sub> and other alkaline/rare earth compounds
  - Bi<sub>2</sub>Te<sub>3</sub> and PbTebased advanced materials
- Skutterudites
- Half-Heusler
- Silicides
- Tetrahedrite

#### **Devices:**

Design, Performance testing and modeling







## Advanced materials and interfaces

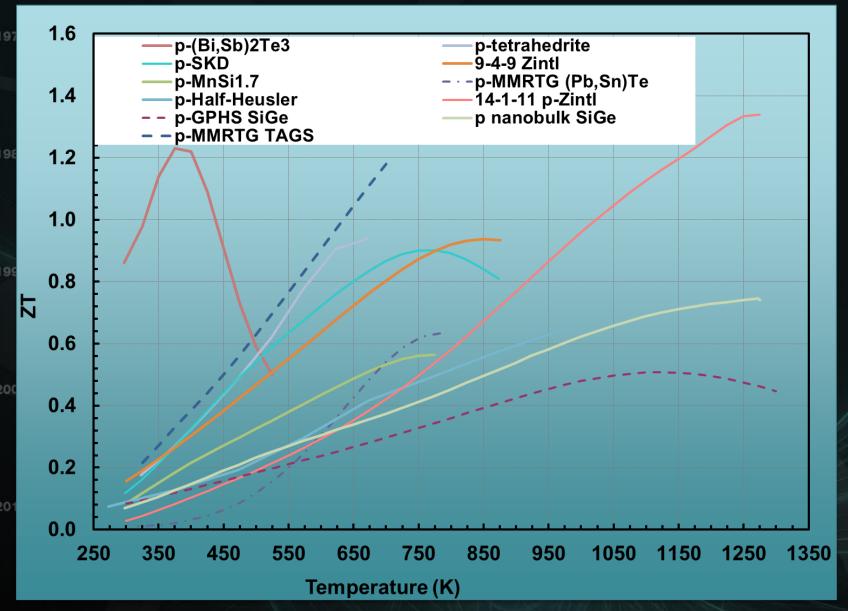
- Opacified aerogels
- Composites

Pre-Decisional for Discussion Only

# Next Generation RTG Segmented Couple Configurations

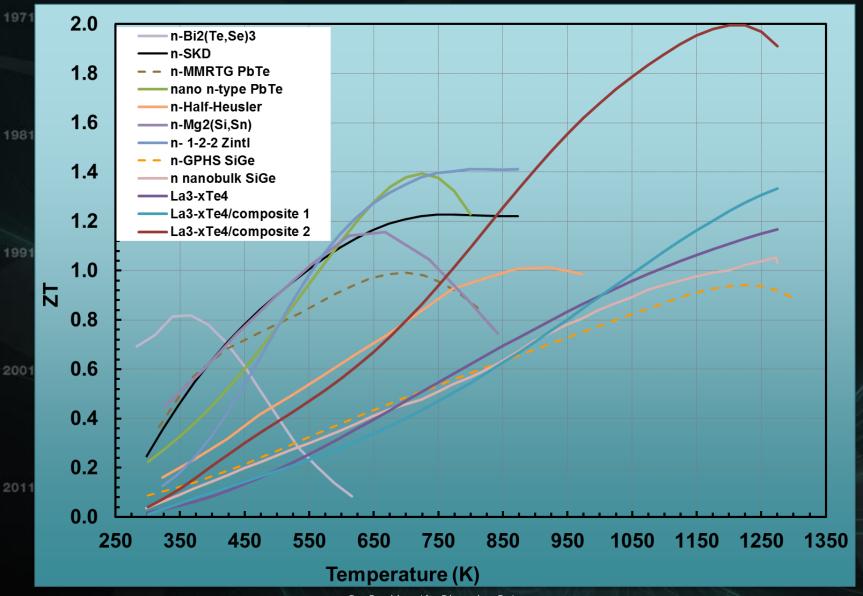
Configuration		n		р				
	Low	Mid	High	Low	Mid	High		
1		1-2-2 Zintl	La <sub>3-x</sub> Te₄ composite		9-4-9 Zintl			
2			La <sub>3-x</sub> Te₄					
3	D: T 0	SKD	La <sub>3-x</sub> Te₄ composite	D: 01 T	SKD			
4	Bi <sub>2</sub> Te <sub>3-x</sub> Se <sub>x</sub>		La <sub>3-x</sub> Te <sub>4</sub>	Bi <sub>2-x</sub> Sb <sub>x</sub> Te <sub>3</sub>		14-1-11 Zintl		
5		Mg <sub>2</sub> Si <sub>1-x</sub> Sn <sub>x</sub>			tetrahedrite			
6		n-Half Heusler	La₃ <sub>-x</sub> Te₄		p-Half Heusler			
7		PbTe	composite		TAGS			
8		nano PbTe						
9		Mg <sub>2</sub> Si <sub>1-x</sub> Sn <sub>x</sub>	nano SiGe		MnSi <sub>1.7</sub>	nano SiGe		
10			La <sub>3-x</sub> Te₄ composite			14-1-11 Zintl		
11			La <sub>3-x</sub> Te₄			14-1-11 Zintl		
12			Nanobulk SiGe			Nanobulk SiGe		
13	$Bi_2Te_{3-x}Se_x$			Bi <sub>2-x</sub> Sb <sub>x</sub> Te <sub>3</sub>				
14	Bi <sub>2</sub> Te <sub>3-x</sub> Se <sub>x</sub>		La <sub>3-x</sub> Te₄ composite	Bi <sub>2-x</sub> Sb <sub>x</sub> Te <sub>3</sub>		14-1-11 Zintl		
15		SKD			SKD			
16		PbTe			TAGS			
17	D: To Co	Mg <sub>2</sub> Si <sub>1-x</sub> Sn <sub>x</sub>		D: Ch To	tetrahedrite	14-1-11 Zintl		
18	Bi <sub>2</sub> Te <sub>3-x</sub> Se <sub>x</sub>	n-HH	La. Ta	Bi <sub>2-x</sub> Sb <sub>x</sub> Te <sub>3</sub>	р-НН			
19		PbTe	La <sub>3-x</sub> Te₄		·			
20		nano PbTe			TAGS			
21			La <sub>3-x</sub> Te <sub>4</sub>			14-1-11 Zintl		

## Performance of p-type material candidates



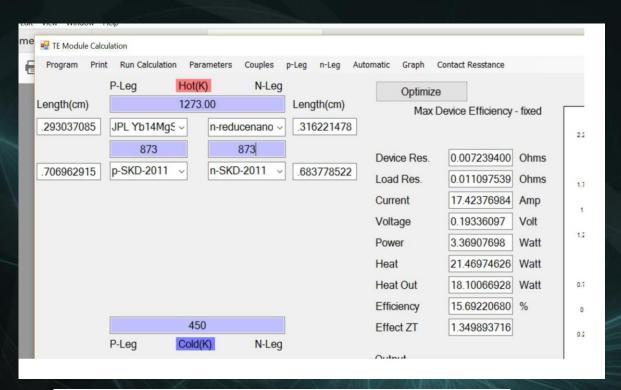
## Performance of n-type material candidates

1961



## Couple-level Performance Predictions

- JPL analytical tool for optimizing segmented couple configurations for various operating conditions
- Calculations were based on "perfect" devices with no parasitic interface and interconnect resistances



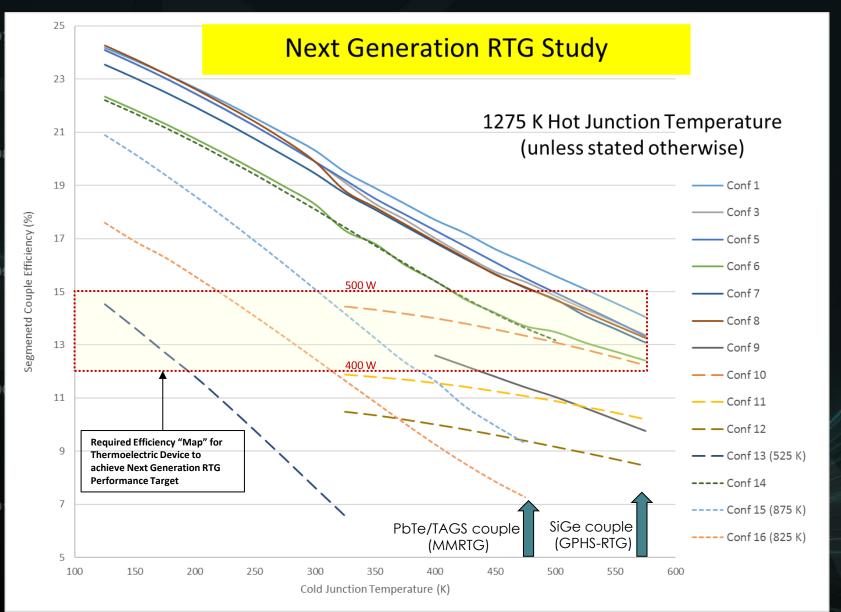
<sup>[4]</sup> Snyder, G.J. and T.S. Ursell. 2003. "Thermoelectric Efficiency and Compatibility," *Phys. Rev. Lett.*, 91 (14), 148301.

1961

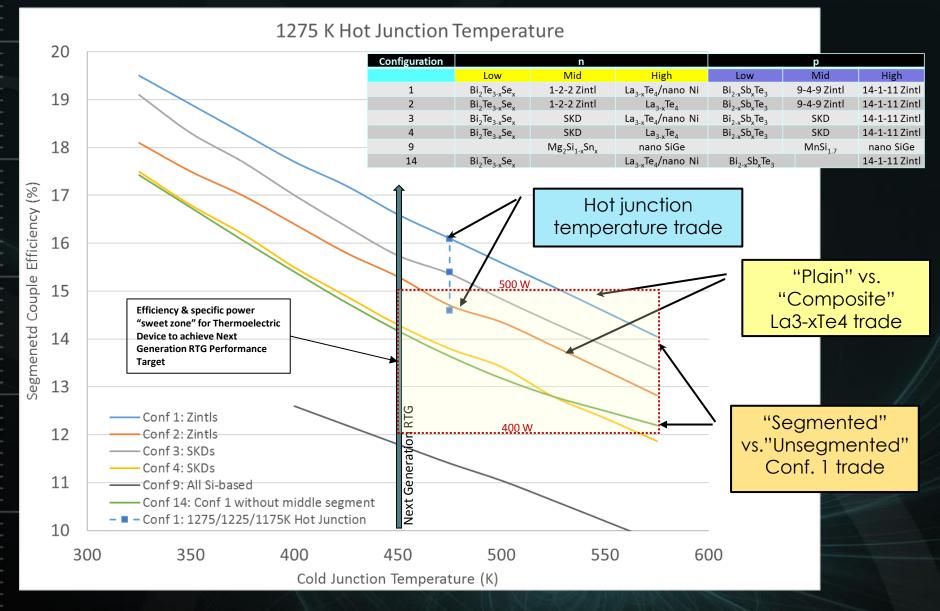
1991

2001

## Performance of Next Generation RTG Couple Configurations Candidates

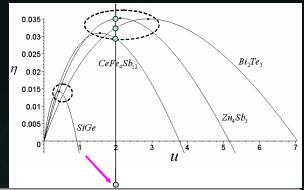


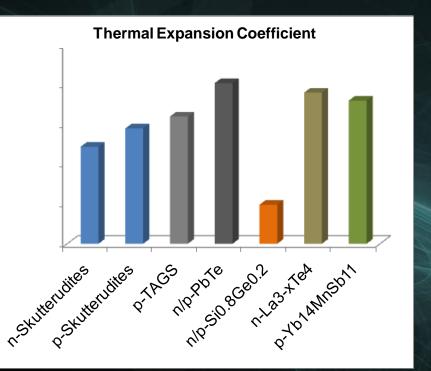
## Performance of Next Generation RTG Couple Configurations Candidates (2/2)

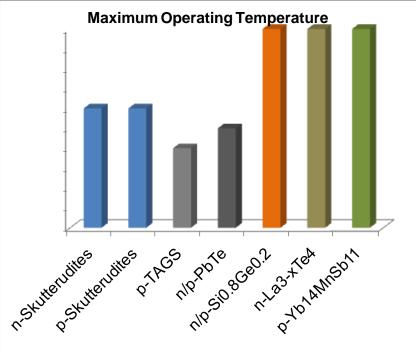


## TE Materials Selection for Segmented Device

- Si-Ge alloys have much lower coefficient of thermal expansion (CTE) and their TE properties are not compatible with those of other candidate materials
  - Would require cascading
  - Not practical for RTG applications
- Zintl and La3-xTe4 best high temperature materials for segmented devices
  - Reasonable CTE match with other TE materials
  - Good TE compatibility with skutterudites, PbTe, TAGS







## Device Component Technology Survey

- Conducted a survey of device technology development for relevant materials under consideration
- TRL > 2 requires initial development and testing of components and devices
  - Requires at a minimum development of basic metallization schemes
  - Some of these materials have been successfully integrated into devices
  - All of the recent work to date on materials and components for operation above 1000 K has been carried by or in collaboration with NASA/JPL
- Higher TRL would provide extended (months to years) performance data on:
  - TE Materials transport properties

2011

- Ability to control sublimation rate to acceptable level
- Demonstration of slow degradation rate kinetics for key interfaces in device
- Ability to integrate with thermal insulation
- Ability to operate in relevant environment

# Thermoelectric Technology Scorecard

ıtion	Segment TRL TRL Efficiency		Sublimation rating		Segmentation Ratings			Hot Side Metallization Rating		Score								
Configuration	Segments per Leg	n-type	p-type	Config.	1275K T <sub>hj</sub> 450K T <sub>cj</sub>	875K T <sub>hj</sub> 450K T <sub>cj</sub>	Efficiency 875K T <sub>hj</sub> 350K T <sub>cj</sub>	TE Cavity Atmosphere rating	n-leg	b-leg	CTE mismatch	Complexity	n-leg Top/Mid Segment Interface	p-leg Top/Mid Segment Interface	n-leg	b-leg	Weighted	Unweighted
1	3	9/2/2	9/2.5/3.5	1	16.5			4	4	3	4	2	3	4	4	3	273	49
2	3	9/2/3.5	9/2.5/3.5	1	15.3			4	4	3	4	2	3	4	4	3	263	47
3	3	9/4/2	9/4/3.5	2	15.8			4	4	3	1	2	2	2	4	3	254	43
4	3	9/4/3.5	9/4/3.5	3	14.3			4	4	3	1	2	2	2	4	3	256	42
5	3	9/3/2	9/3/3.5	0	16.1			4	1	3	3	2	1	1	4	3	223	38
6	3	9/3/2	9/3/3.5	0	14.3			4	4	3	1	2	3	3	4	3	220	41
7	3	9/9/2	9/9/3.5	1	15.6			2	3	3	3	2	3	3	4	3	243	43
8	3	9/9/2	9/9/3.5	1	15.6			2	3	3	3	2	3	3	4	3	243	43
9	2	3/2.5	3/2.5	0	11.8			4	1	4	1	3	3	3	1	1	175	33
10	1	2	3.5	2	13.8			4	4	3	4	3	4	4	4	3	271	49
11	1	3.5	3.5	3.5	11.3			4	4	3	4	4	4	4	4	3	275	49
12	1	2.5	2.5	2.5	9.8			4	4	4	4	4	4	4	1	1	233	42
14	2	9/2	9/3.5	1	14.0			4	4	3	4	3	3	3	4	3	253	46
17	3	9/3/3.5	9/3/3.5	0	14.5			4	1	4	3	2	1	1	4	3	214	38
18	3	9/3/3.5	9/3/3.5	0	13.1			4	4	3	1	2	3	3	4	3	211	40
19	3	9/9/3.5	9/9/3.5	1	14.0			2	3	3	3	2	3	3	4	3	230	41
20	3	9/9/3.5	9/9/3.5	1	14.3			2	3	3	3	2	3	3	4	3	232	41
21	2	9/3.5	9/3.5	2	12.0			4	4	3	4	3	3	3	4	3	251	45
		Weighting		14	8	8	8	5	4	<u> </u>	6	3	3	3	4	4		
		Troighting		<1	,				7	7	≥30%	•	-	-	7	-		
				1≤x<2	<12%	<12%	<12%	Ar only	High: ≥10 <sup>-4</sup> g/cm <sup>2</sup> /hr ≥30%  Medium: 10 <sup>-4</sup> >x>10 <sup>-5</sup> 20≤x<30 g/cm <sup>2</sup> /hr				_	<230	<42			
				2≤x<3	12≤x<14 %	12≤x<14 %	12≤x<14 %	Vacuum/ Ar	Low: 10 <sup>-5</sup> >) g/cm <sup>2</sup> /hr		10≤x<20 %	Minor Development Effort Required (1 -2 Years)		ears)	230≤x<2 50	<mark>42≤x&lt;47</mark>		
				≥3	≥14%	≥14%	≥14%		Very Low: s g/cm²/hr	≤10-6	<10%	Minimal Development Required (≤ 1 year)			≥250	≥47		

## Results – TE Maturity

> 10% target

Configuration	# Segments	~Couple Efficiency at T <sub>cj</sub> 450K	TRL Materials n p		TRL of Configuration	~ Generator Efficiency at BOL (16 GPHSs)
1	3	17	9/2/2	9/2.5/3.5	1	14.5
2	3	15	9/2/3.5	9/2.5/3.5	1	12.8
3*	3	16	9/4/2	9/4/3.5	2	13.6
4*	3	14	9/4/3.5	9/4/3.5	2.5	12.0
10	1	14	2	3.5	2	12.0
11	1	11	3.5	3.5	3.5	<del>9.4</del>
14	2	14	9/2	9/3.5	2.5	11.9
21	2	12	9/3.5	9/3.5	2.5	10.2

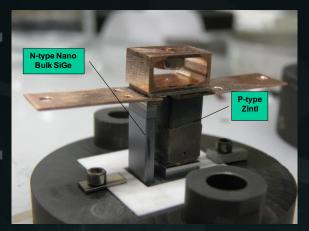
- Choose ~4 (1, 3, 4, 14) and raise TRL to 3/4
- Prefer 1- and 2-segment couple configurations (no cold side Bi<sub>2</sub>Te<sub>3</sub>-based segments)
  - In this case TC-14 is identical to TC-10

# Next Generation RTG Segmented Couple Configurations

Configuration		n	р			
	Mid	High	Mid	High		
1	1-2-2 Zintl	La <sub>3-x</sub> Te <sub>4</sub> /composite	9-4-9 Zintl	14-1-11 Zintl		
3	SKD	La <sub>3-x</sub> Te <sub>4</sub> /composite	SKD	14-1-11 Zintl		
4	SKD	La <sub>3-x</sub> Te <sub>4</sub>	SKD	14-1-11 Zintl		
14		La <sub>3-x</sub> Te <sub>4</sub> /composite		14-1-11 Zintl		



## Device Configurations in Development Under NASA RPS Thermoelectric Technology Development



Project



Hot Shoe/
Heat Collector

Control

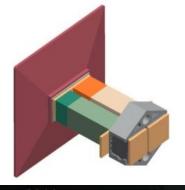
Zintl
Leg

Cold Shoes/
Heat Sink

Zintl (Yb<sub>14</sub>MnSb<sub>11</sub>) / La<sub>3-x</sub>Te<sub>4</sub>
Couple (2009-2010)

Zintl (Yb<sub>14</sub>MnSb<sub>11</sub>) / NanoSiGe Couple (2007-2009)

1275-475 K Target operating temperatures





n-La<sub>3-x</sub>Te<sub>4</sub> (bare)

n-SKD with sublimation suppression coating



14-1-11Zintl/SKD // La<sub>3-x</sub>Te<sub>4</sub>/SKD Segmented Couple (2011)

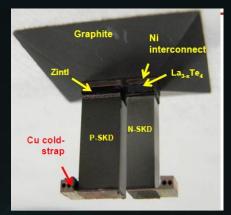
14-1-11 Zintl/9-4-9 Zintl // La<sub>3-x</sub>Te<sub>4</sub>/1-2-2 Zintl Segmented Couple (ECD of 9/2017)

**Cantilevered** 

Segmented Couples and Multicouples (goal – TRL 3/4 by end of FY19)

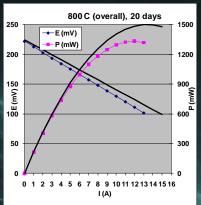
# Segmented Couple Demonstrations (Designed for Vacuum and/or Inert Gas Operation)

- Spring-loaded and cantilevered configurations fabricated and tested to date
- Hot junction temperatures up to 1275 K
- Cold junction temperatures down to 475 K
- Segmented couple efficiencies from 10% (975 K) to 15% (1275 K)



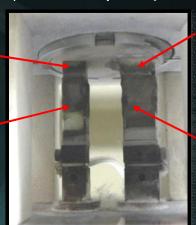
ATEC segmented couple (1073K – 473 K operation)





n-La<sub>3-x</sub>Te₄ (bare)

n-SKD with sublimation suppression coating



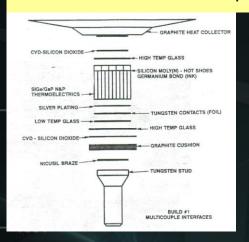
p-Zintl with sublimation suppression coating

n-SKD with sublimation suppression coating

T <sub>H</sub> /T <sub>C</sub> (K)	1275 / 475	1075 / 475	975 / 475	875 / 475
Predicted TE Couple Efficiency	13.7%	11.2%	10.0%	9.3%
Demonstrated Efficiency (BOL)	14.8%	11.0%	10.0%	9.3%

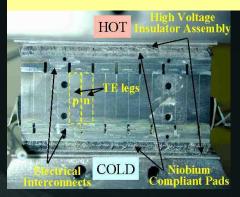
# Mechanically Compliant High Temperature TE Multicouple Technologies: Past & Present NASA Efforts

#### MOD-RTG SiGe Multicouple Technology (1980s)



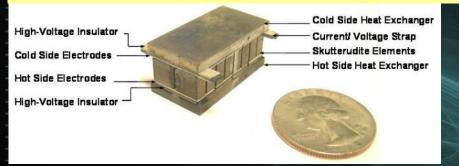
Designed for radiative coupling with GPHS

#### SP-100 SiGe Multicouple (1990s)



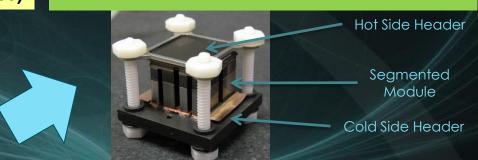
Designed for conductive coupling with flat plate HXs,

Skutterudite Multicouple Developed at JPL under NASA/SMD In-Space Propulsion Program (2004-2005)



Designed for conductive coupling with flat plate HXs – 873 - 473 K operating temperature range

Segmented Multicouples developed for space and terrestrial power systems (2011-2014)



Designed for conductive coupling to GPHS or radiative coupling (solar) – 1273 - 473 K operating temperature range

### NextGen RTG - TE Tech Downselect is in current RPS/TTDP Portfolio

TTDP current TE materials portfolio covers thermocouple configurations downselected ithis n study



- 14-1-11 Zintls
- Skutterudite
- 9-4-9 Zintl

### n-type materials:

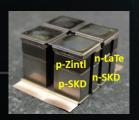
- La<sub>3-x</sub>Te<sub>4</sub> and related composites
- Skutterudite
- 1-2-1 Zintl

TTDP currently developing unsegmented and segmented device technologies based on these materials





Configurations 1, 2, 3 and 4 without bottom Bi<sub>2</sub>Te<sub>3</sub>-alloy low temperature segment







More limited efforts to date on multicouple technology by TTD

Proof-of-principle Segmented Module (configuration 4)

## Summary & Recommendation

- Evaluated 3-Segment, 2-Segment and 1-Segment Configurations
  - Materials-level efficiencies as high as 17% for 450 K cold junction temperature and 1273 K hot junction temperature
  - Efficiency decreases (model predicted) as number of segments decreases
  - System degradation rate of 1.9% assumed for all configurations
  - Risks decreases as number of segments decreases
- 8 different TE configurations modeled in generator concepts
  - Several of these meet the > 12% efficiency target for thermoelectric couples
  - These configurations are under development by NASA

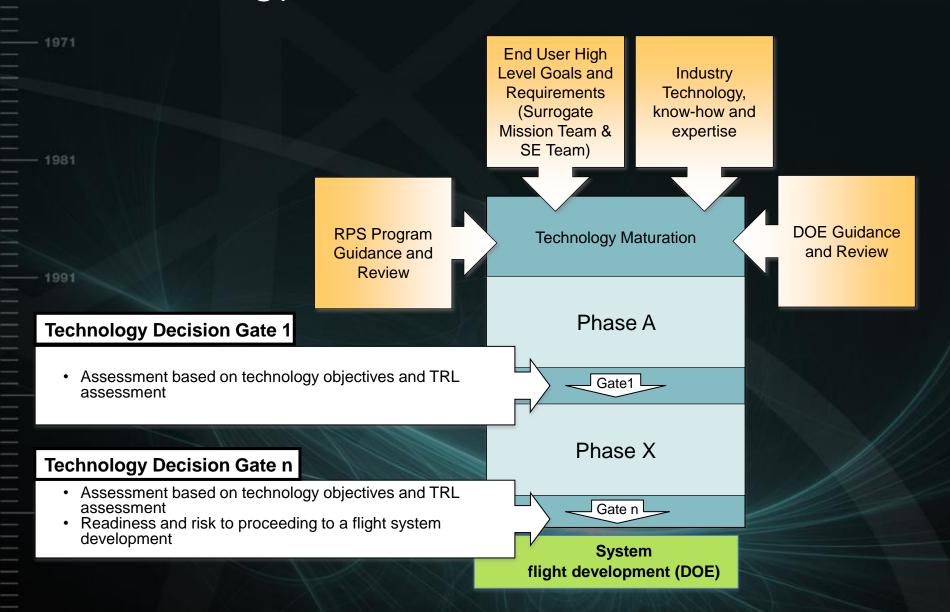
1971 RADIOISOTOPE POWER SYSTEMS PROGRAM NASA CONCEPTUAL PLAN **FORWARD** 1991 2001 2011 Pre-Decisional for Discussion Only 2021

## Next-Generation RTG RFI and Technology Maturation Plans

- Technology maturation process planned to mature technology and prepare for flight system development
  - Based on technology development and maturation lessons learned
  - Grounded in Next-Generation RTG Study

- System-level requirements development in progress with heavy flight center participation
- Known NASA(JPL) potential technologies will continue to be matured for industry consideration
- Technology development requires technology to be ready to proceed such that a Next-Generation
   Qualification Unit could be ready by 2028

# RPS Program's Technology Transfer and Maturation Model



## What Are We Looking For?

- Potential technologies to lead to a Next-Generation RTG that would meet the top level driving requirement
- Dialog with the community on industry needs regarding NASA TE technology investments
- Response to the RFI
- Feedback on draft RFP

2001

## Next-Gen RTG Top Driving Requirements

- System designed to operate in vacuum
- System designed to be modular
  - Requires process for modular qualification
- System (16 GPHS) provides at least 400 We at BOL with a goal of 500 We
- System (16 GPHS) mass is 60 kg or less
- System degradation rate, including fuel degradation, projected to be 1.9%
  - To be rewritten in terms of EODL power
- System to be designed to be upgraded with new TCs as technology matures

## Plan Forward

- System concept driven TE technology plan
- Technology includes TE technology and associated technology (e.g. insulation)
- JPL materials and TE information to be made available
  - Details being worked
- Three Technology Phases with Gates
  - Phase I Technology Advancement
  - Phase II Technology Maturation
  - Phase III Government evaluation phase
- If technology is deemed mature to proceed DOE System Development Contract to Qualification unit by 2028

## Timeline

- Preparation & Discovery Phase June 2017 to March 2018
  - RFI (Fall 2017)\*
  - Acquisition Strategy
  - Industry Day(s) (Fall 2017)\*
  - Draft functional requirements and technology requirements
  - Continued investment in NASA potential TE technology
- Technology Phase March 2018 to October 22\*
  - RFP
  - Multiple Awards
  - Technology development anchored to potential Next Generation RTG system concept
  - Assessment of technology readiness for system development
- System Development Phase to Qualification Unit 2023 to 2028

\*Tentative
DOE Led Phase

## Summary of Draft RFI Requests

- Availability or potential availability of TE technology options that could be utilized in a modular, 50-500 We power system
- Understanding of current device(s) and state of development
- TE device operation. Configuration, mass, performance, operational temperature range, and fault tolerance.
- Number of applicable units produced, demonstrated life and reliability, risks to achieve long operational life
- Scalability, if required. Projected performance
   correlated with heat source degradation
- Experience with production of space-flight, nuclear hardware, materials, components, devices, converters, processes, Integration, test, and QA

## Summary of Information Requested

- What company assets/expertise will be utilized for this activity
- What partnerships; i.e. other industry, NASA, other will be used for the technology development, hardware production, and test
- How will this capability be sustained during periods of non-use by NASA
- Other

2001

## Radioisotope Power Systems Program

Q&A

Find these charts at http://rps.nasa.gov





Glenn Research Center
Jet Propulsion Laboratory
Applied Physics Laboratory



Idaho National Laboratory
Los Alamos National Laboratory
Oak Ridge National Laboratory
Sandia National Laboratories

http://rps.nasa.gov rps@nasa.gov



## **MMRTG** Primer

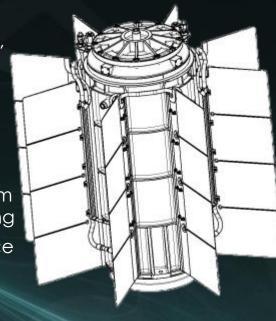
• The Multi-Mission Radioisotope Thermoelectric Generator, or MMRTG, is powering Curiosity and is the baseline power system for Mars 2020 rover

Converts heat produced from the decay of plutonium dioxide into DC power

- Power at launch is >110W DC, quiet
- Mass is ~45kg

2021

- Operates in vacuum and planetary atmospheres
- Roughly speaking the generator envelope is a 60 cm diameter cylinder x 60 cm long
- Mounts using a 4-bolt interface
- Thermal output is ~1880Wth, BOL
- Cooling tubes are optional
- Can be painted in black or white
- White paint matches optical properties of MMRTG on Curiosity



**MMRTG** 

- Design is rugged and passive
- Series-parallel electrical circuit for increased reliability
- Does not require in-flight commanding; nor in-flight maintenance
- The environmental requirements include qualification to ATLAS and DELTA LV levels (0.2g^2/Hz.)
- Nuclear Launch Safety basis was established by MSL

As Measured F1 MMRTG Mass = 44.79 kg

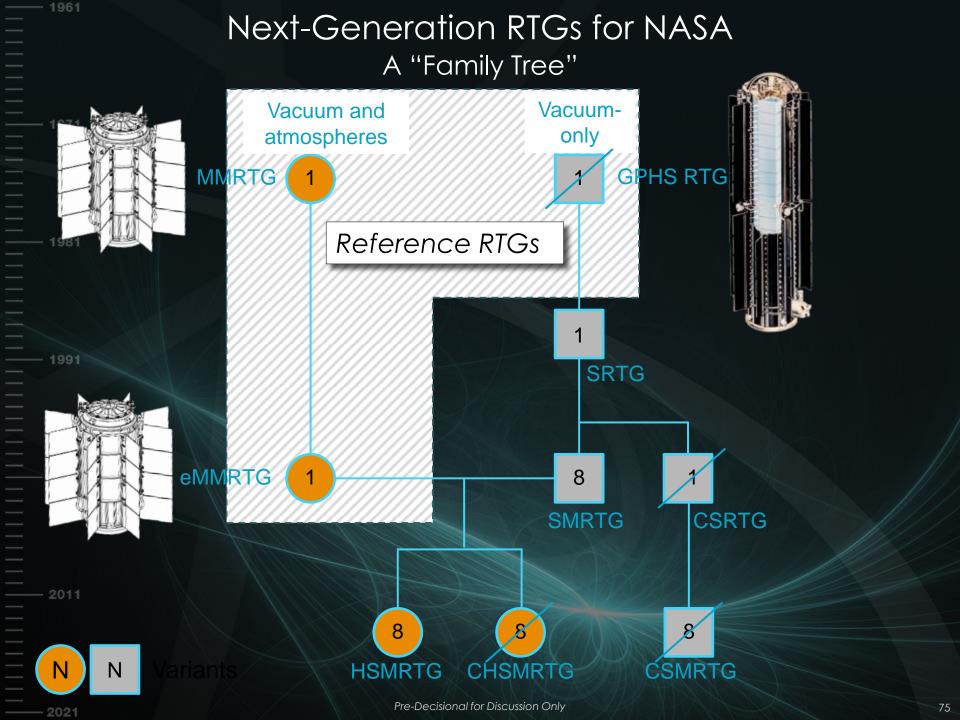
## Next-Generation RTGs for NASA Mission Analyses (MA)

- A few additional requirements flowing from the missions flown and studied
- Mission Length
- Radiation
- Descent and Landing
- Micrometeoroids
- Atmospheric pressure and atmospheric constituents
- Environmental temperatures

## Next-Generation RTGs for NASA Mission Analyses

- Lastly, where mission analyses did not suffice, requirements came from reference RTGs: GPHS-RTG, MMRTG, and eMMRTG
- Requirements were captured for:
  - Launch Vehicle Environments (Random vibe, shock)
  - Maximum dimensions (Height, diameter)
  - Neutron emissions
  - Ground processing-related requirements
  - Fuel thermal inventory
  - Fueled storage life

- Allowable Flight Temperatures and Voltages
- Qualification requirements



## Next-Generation RTGs for NASA Concepts

### Vacuum

 Can reliably fulfill need for Flyby/Orbiter and can be used to for Ocean World exploration

### Cold

- Requires three-segment TEC
- Higher risk to develop
- Conceived to benefit colder environments but is of little benefit and is NOT necessary

### Hybrid

- Requires hermetically sealed TEC compartment
- Complexity in design which is more complex with modularity
- Additional risks and costs. With investment in eMMRTG, not necessary.

### Modular

- Unique housing size for each variant
- Allows for mission flexibility without significant risk

## Historical RTG-Powered U.S. Missions

Mission	RTG type (number)	TE	Destination	Launch Year	Mission Length	Power Level*
Transit 4A	SNAP-3B7(1)	PbTe	Earth Orbit	1961	15	2.7
Transit 4B	SNAP-3B8 (1)	PbTe	Earth Orbit	1962	9	2.7
Nimbus 3	SNAP-19 RTG (2)	PbTe	Earth Orbit	1969	> 2.5	~ 56
Apollo 12#	SNAP-27 RTG (1)	PbTe	Lunar Surface	1969	8	~ 70
Pioneer 10	SNAP-19 RTG (4)	PbTe	Outer Planets	1972	34	~ 160
Triad-01-1X	SNAP-9A (1)	PbTe	Earth Orbit	1972	15	~ 35
Pioneer 11	SNAP-19 RTG (4)	PbTe	Outer Planets	1973	35	~ 160
Viking 1	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	> 6	~ 84
Viking 2	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	> 4	~ 84
LES 8	MHW-RTG (2)	Si-Ge	Earth Orbit	1976	15	~ 308
LES 9	MHW-RTG (2)	Si-Ge	Earth Orbit	1976	15	~ 308
Voyager 1	MHW-RTG (3)	Si-Ge	Outer Planets	1977	40	~475
Voyager 2	MHW-RTG (3)	Si-Ge	Outer Planets	1977	40	~475
Galileo	GPHS-RTG (2)	Si-Ge	Outer Planets	1989	14	~ 574
Ulysses	GPHS-RTG (1)	Si-Ge	Outer Planets/Sun	1990	18	~ 283
Cassini	GPHS-RTG (3)	Si-Ge	Outer Planets	1997	20	~ 885
New Horizons	GPHS-RTG (1)	Si-Ge	Outer Planets	2005	12 (17)	~ 246
MSL	MMRTG (1)	PbTe	Mars Surface	2011	6 (to date)	~ 115
Mars 2020**	MMRTG (1 baselined)	РЬТе	Mars Surface	2020	(5)	> 110

"Apollo 12, 14, 15, 16 and 17 \*\*Planned \*Total power at Beginning of Mission (W)

From a few watts up to ~ 900 W, up to 37 years of operation (and counting)

# Draft TRLs for RTG Technology

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TRL	Definition from NPR 7123.1e [1]	Completion Criteria RTG TE	Mission Requirements	Performance/ Function	Fidelity of Analysis	Fidelity of Build	Level of Integration	Environment Verification			
1	observed and reported	Temperature-dependent TE properties as a function of composition, microstructure and morphology	of missions	TE properties as a function of temperature; basic thermal and chemical stability assessment.	Physics of transport properties identified	N/A	Basic lab-scale material samples	High temperatures, Vacuum/inert gas			
2	Technology concept and/or application formulated	TE property optimization and reproducibility – basic physical properties measured	Generic class of missions	ZT values; device-level performance prediction; Initial estimate for upper range of operating temperatures	Transport property model developed; predicted conversion efficiency in relevant temperature range	N/A	Basic lab-scale material samples	High temperatures, Vacuum/inert gas			
3	Analytical and/or experimental proof-of- concept of critical function	Initial validation of TE properties at device level; high temperature physical properties and thermal stability documented	Generic class of missions	Proof-of-Concept couple BOL performance matches initial prediction; initial estimate for thermal/mechanical stability	Efficiency prediction based on BOL performance; Initial testing for degradation mechanisms	Low-fidelity TE couple and/or module; initial tech development of interfaces, hot/cold shoes	Thermally insulated stand- alone TE device	High temperatures, Vacuum/inert gas			
4	Component and/or breadboard validated in laboratory environment	Documented extended test performance under relevant conditions for components (TE materials, interfaces, dielectrics, insulation)	Generic class of missions	Proof-of-Concept couple BOL and extended performance; Component level life testing completed; degradation mechanisms identified	Lifetime performance prediction models developed at the component levels through accelerated testing;	Medium fidelity: RTG- configured TE couples/modules with prototypic hot/cold shoes	Component/ TE couple/ module	High temperatures, Vacuum/inert gas testing of TE devices with prototypic thermal insulation			
5	Component	Documented extended	Generic or	Couple/module BOL	Lifetime performance	Medium fidelity: RTG-	TE couples/	High			
	and/or brassboard validated in relevant environment	test performance under relevant conditions for couples/modules. Documented definition of scaling requirements	specific class of missions	and extended performance under nominal/accelerated conditions broadly meet target performance goals	prediction models developed at the device level through accelerated testing; Initial prediction for system level	configured TE couples/modules with realistic interfaces and thermal packaging/mechanic al support	modules	temperatures, Vacuum/inert gas testing of TE devices with prototypic thermal insulation and converter parts			
6	System/ subsystem model or prototype demonstrated in a relevant environment	Documented extended test performance under relevant conditions for modules. Documented definition of flight system requirements	Generic or specific class of missions	Module BOL and extended performance under nominal/accelerated conditions meet target performance goals	Lifetime performance prediction models validated at the device level through accelerated testing; updated prediction for system level.	High fidelity: electrically heated performance demonstrator (EPD) prototype that addresses all couple/module critical scaling, packaging and integration issues	TE modules integrated into EPD (can be discrete array of couples)	High temperatures, Vacuum/inert gas testing of TE devices with prototypic thermal insulation and converter parts			